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Issues for Radiation Assurance Validation at Jupiter's Moon, Europa.

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Missions to Europa and other moons of Jupiter will experience the most severe radiation environment in the Solar System outside the Sun. Although several spacecraft have rapidly passed through this environment, no spacecraft has been flown continuously in such an environment. The proposed mission to Europa, however, will spend a continuous month or longer in this environment. As mission plans have proceeded, new assurance issues have arisen.

These issues include: A factor of two or more uncertainty in the radiation environment produces factor of two or more uncertainty in mission duration, now planned at one month. Large uncertainty in the very high-energy proton and electron environment causes large uncertainty in the effectiveness of radiation shielding, and produces extreme launch-mass penalties. Rapid dose degradation of electronics creates requirement for more rapid data collection, but faster instruments may be more sensitive to radiation. A single safe-hold could doom the short mission as radiation continues to degrade systems while ground personnel devise fixes. Thus the safe-hold process becomes a dramatic part of the assurance equation and must be streamlined. Uncertain radiation charging and discharging test results indicate ESD pulsing amplitudes and pulsing rates threaten the newer ESD-sensitive electronics. Proposed ESD solutions are only partially tested and are unfamiliar to most systems designers.

As a result of these issues, risk/design tradeoffs will be difficult to quantify for the Europa mission and pose a unique challenge for radiation assurance techniques.

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OUTLINE

HIGH RADIATION MISSIONS

FAILURE MODES

FAILURE CAUSES
- *Total dose*
- *Displacement damage*
- *Electric charging/discharging*
- *Single events from Cosmic rays*

GROUND TESTING TO ESTABLISH ASSURANCE

IN-FLIGHT MONITORING OF HARDWARE??

THE PREDICTED ENVIRONMENT

THE ACTUAL ENVIRONMENT

LESSONS LEARNED FROM THE GALILEO MISSION TO JUPITER

HIGH RADIATION MISSIONS

Planetary magnetic field is required.

Energetic electrons and protons become trapped in the magnetic field.

Jupiter is most severe, Earth is next most difficult. Saturn maintains a weak radiation zone.

Elsewhere, solar storms may create transient H.E. Proton flux

Rare Very High Energy Cosmic Rays are everywhere.

INDICATIONS THAT JOVIAN RADIATION BELTS ARE VARIABLE.

DATA RELATED TO DOSE ON GALILEO (as of 2 March 2000)

ORBIT	USO F-shift Hz	Relative Scanner Peak Current	Relative Scanner Current, near 9-10 Rj	Ratio of EPD >11MeV electron flux to Scanner Current at 9-10 Rj	Estimated krad 2.2 g/cm2
JOI-0	No data	5300			53
1-G	< .05	33			1.7
2-G	.09	25			2.4
3-C	.30	230	20.06	625	7.9
4-E	.25 ?	130	141.59	778	8.3
5	?		64.46	702	9.1
6-E	.20	150	44.67	716	8.8
7-G	.29	180			8.3
8-G	.20	140	44.33	508	7.2
9-C	.38	170	95.33	635	1.8
10-C	.33	140	54.31	634	7.7
11-E	.26	140	28.30	680	9.4
12-E	.87	270	223.25	739	8.8
13-E		230	53.13	666	8.8
14-E		190	127.07	481	8,8
15-E		265	43.95	787	8.8
16-E		200	50.53	618	8.8
17		109	62.67	425	10.0
18		182	82.19	592	9.8
19		120	68.28	740	8.0
20		156	55.45	632	7.4
21		345	149.15	694	23.3
22		1300	15.63	924	23.2
23		580	55.13	636	28.9
24		950	71.58	661	40.1
25		850			38.3
26		700			36.6

The data in the Table is a mixture of rate data and time-integrated data. Further work is needed to put the data sets into similar units so that comparison is more precise. All measures of dose indicate that the particle fluxes in the belts are changing orbit to orbit and therefore the belts are not static. The predicted orbital krads behind 2.2 g/cm2 is based on the static Jovian belt model. The scanner current, which is a photomultiplier tube that also measures dose rate, is a measure of dose rate deep inside the spacecraft, and correlates well with the Energetic Particle Detector measured fluxes >11 MeV. It is probably possible to calibrate the scanner current into an absolute measure of dose rate at one depth in the spacecraft. This would improve estimates of deep penetrating dose for Europa.

FAILURE MODES

ALMOST ALWAYS: A device fails to operate within specification, therefore circuit/system degrades or dies.

CREEPING TOWARDS OUT-OF-SPEC

- Total Dose
- Displacement Damage

TRANSIENT UPSET

- Cosmic Ray Event or HE Trapped Particles
- Electrostatic Discharge

SUDDEN TOTAL FAILURE

- Device Latch-up
- Data bit-flip sends bad command
- Insulator breakdown
- *All can be created by Transient Upset*

SYNERGISM

- Creeping to out-of-spec lowers threshold for transient upset.

ASSURANCE TESTING METHODS

THE IDEAL:

Test the spacecraft or subsystems to radiation specification under all operating conditions

REALITY:

Determine the most sensitive devices
Evaluate radiation sensitivity of devices with limited ground testing
Estimate penetration of radiation to these most sensitive devices.
Predict device degradation and thereby predict system degradation.

AS A RESULT

Testing determines out-of-spec radiation level under only a few operating conditions, usually worst case.

SEVERAL FACTOR-OF-TWO MARGINS BUILT IN

Device operates in space with lower sensitivity to radiation
Circuit operates despite devices going out-of-spec
Spacecraft operates despite circuit going out of spec
Failure can be ignored by reprogramming mission
3-sigma relative to ground-test failure point.

THUS MOST SYSTEMS HAVE OUTLIVED THE "DESIGN-TO" RADIATION FAILURE POINT BY A WIDE MARGIN.

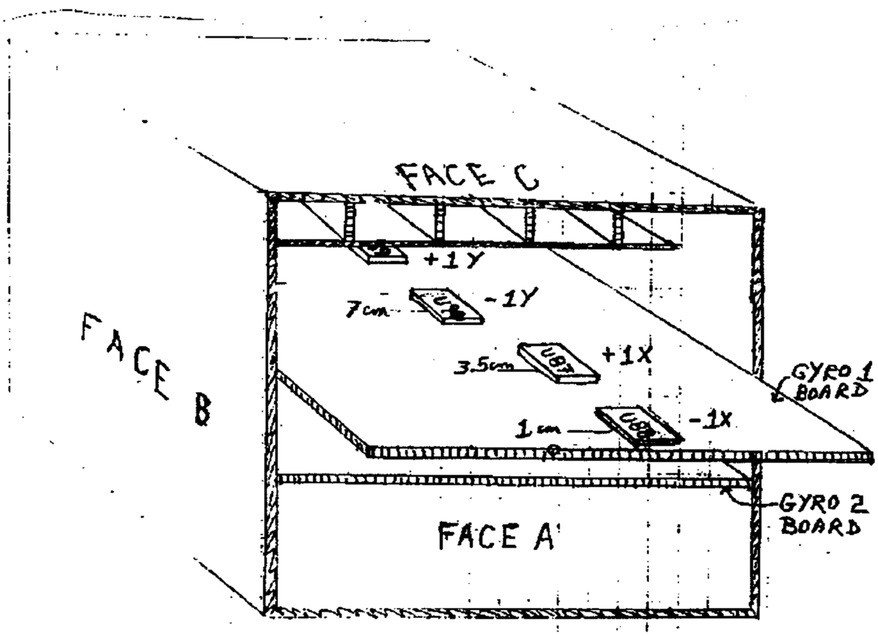
RADIATION EFFECT ACTUALLY MEASURED ON GALILEO

Radiation is known to be the primary cause of degradation of the inertial gyro electronics. Only one device type, the DG-181 JFET switch, has proved to be degrading. The amount of degradation on four DG-181 devices is being monitored. Most other devices can not be monitored to see if degradation occurs.

Ground tests indicate that under operating bias during radiation the source lead leaks current to "ground."

LEAKAGE CURRENT VS. ACCUMULATED DOSE IN GROUND TESTS OF FOUR DG-181 DEVICES.

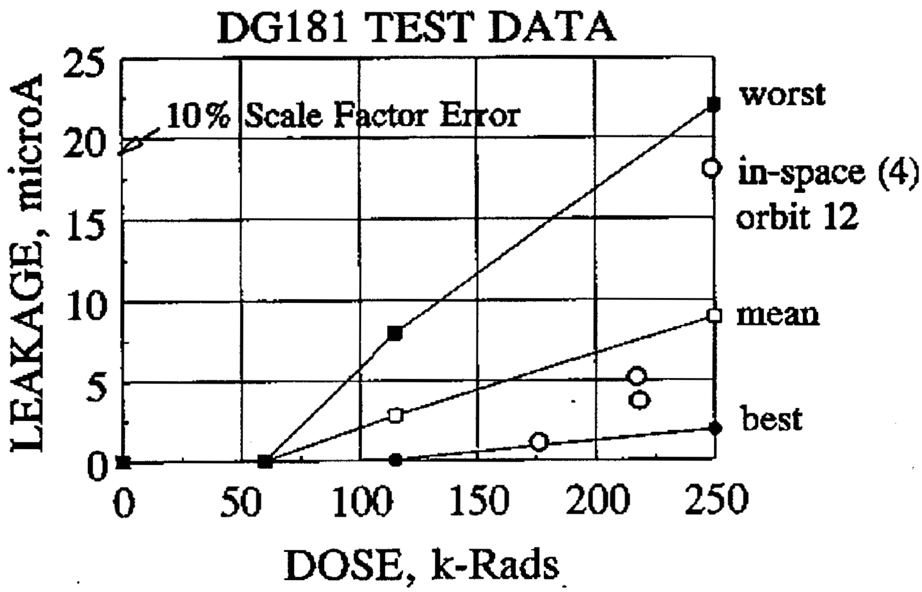
Dose k-Rad	Irrad. Gate Bias, V	Source Leakage, MicroAmps		
		BEST	MEAN	WORST
62	0	0	0	0
62	-1	----	----	----
112	0	.06	4.3	13
112	-1	.05	2.8	8
250	0	1.9	9.3	16
250	-1	1.9	9.0	22



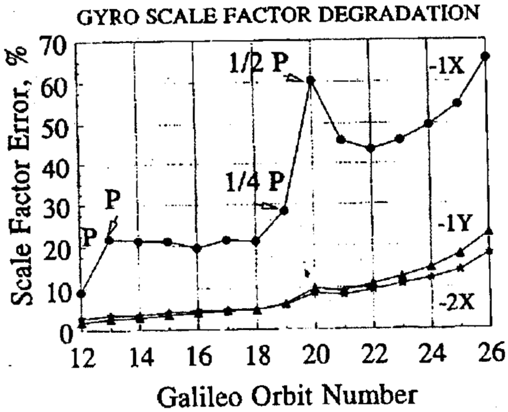
THE GYRO ELECTRONICS BOX. In this view, face A of the aluminum box is removed and the circuit board for gyro #1 is pulled from the box to show the layout of the four DG-181 devices. Radiation from Jupiter's environment impacts faces A, B and C after passing through thermal control surfaces and thin structural plates. The other three faces are well shielded by the bulk of the spacecraft. The –1X axis DG-181 is closest to the irradiated faces and thus receives the most intense radiation. The #2 gyro board is immediately below and identical to the extended #1 board. Degradation of the "minus" devices, such as –1X or –2Y affects the gyro system, but similar degradation of the "plus" devices has not yet affected the system.

The existing model of the Jovian environment combined with a radiation transport code and the mass-model of the spacecraft have been used to estimate the dose received by the four sensitive DG-181 devices. Through twelve orbits, the predicted doses are: -1X = 250 krads, -1Y= 215 krads, -2X = 215 krads and, -2Y = 175 krads. The uncertainty of the transport alone is at least 20%.

The leakage currents induced at Jupiter by radiation may be estimated from the ground radiation tests. At 250 krads the best device developed about 2 microamps leakage, and the worst device developed about 20 microamps leakage. With 18 microamps leakage, the gyro circuits generate an error, called scale factor error, of 10%. The analysis of scale factor error is contained in the **JPL Galileo Europa Mission, Galileo AACS Anomaly Resolution Team Report, 10/15/1998, K. A. Bahrami, et al**.

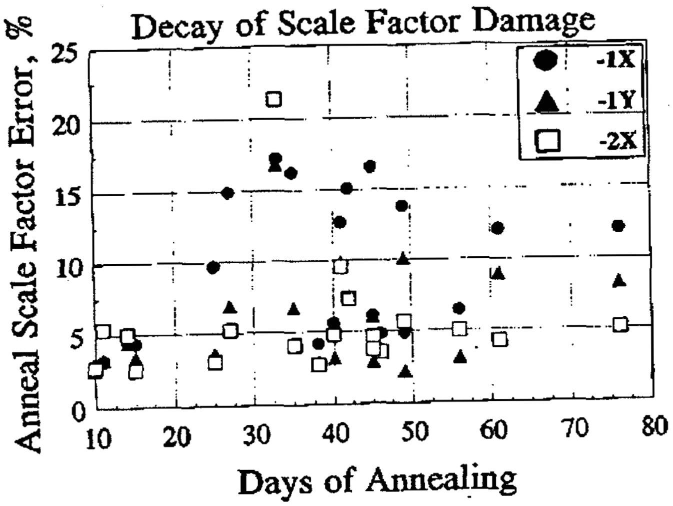


Comparison of estimated in-space dose response with ground test results. The ground test data are connected with the lines. The in-space data for the four devices after orbit 12 is shown by the four open circles. It seems that the four devices tested on the ground varied in dose-response in a manner similar to the four devices flown in space. There is a factor of 10 difference from the worst to the best device in the same lot.



History of three of the four channels that are drifting due to radiation damage. The fourth channel is only drifting a small amount. The first gyro-safehold occurred after orbit 12. Another safehold occurred on orbit 13 because the gyro drifted more than a few percent again. The radiation review team recommended that the gyro electronics be turned off during the period of radiation belt passage, 12 hours during future orbits. The letter "P" in the graph indicates orbits where power was left on. 1/4P indicates power left on during a fourth of the radiation belt pass. From orbit 13 to perhaps 23 it is clear that power-off during radiation belt passage is a preferred mode of operation. Therefore one may improve spacecraft performance by choosing electronics voltages in order to take advantage of device hardness to be obtained at some operating voltages.

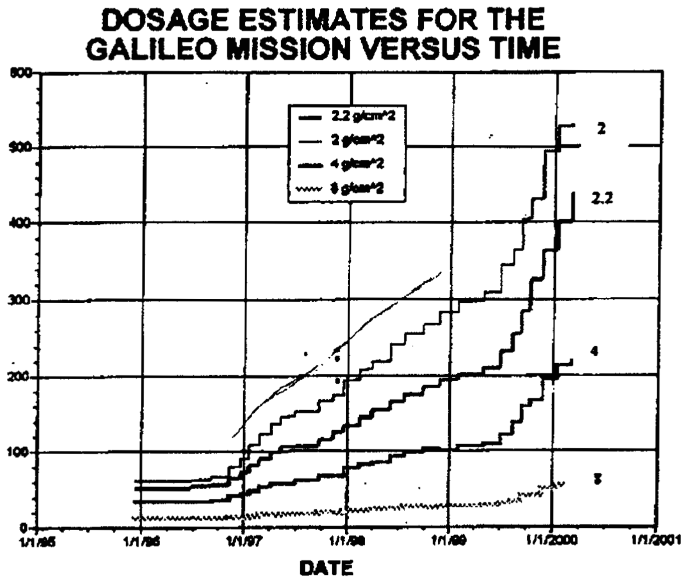
Most device radiation failure levels are specified for the worst case applied voltage. Some devices are far less sensitive to radiation if operated at different voltages. Spacecraft designers should consider taking advantage of this.



Every passage through the radiation belts added an increment of scale factor error. This increment was measured at some time after the 12-hour passage through the belts. The scale factor was again measured from 10 to 77 days later, but before another passage through the belts. Always the increment annealed to some extent. Annealing is important but the data does not provide a clear picture of the rate of annealing.

Perhaps annealing effects can also be used to advantage in spacecraft radiation design. But more extensive ground testing would be necessary in order to evaluate the annealing process.

The pre-flight dose-depth estimates are shown in this graph. The DG181 gyro devices were effectively shielded by only about 1.8 g/cm^2 aluminum because the gyro electronics box is effectively close to the surface of the spacecraft. The predicted dose to



the four DG181 devices is plotted at orbit 12.

The mission was designed to function for more than 6 orbits where 75 krads would be accumulated at 2.2 g/cm^2. Most boxes provided 2.2 g/cm^2 effective shielding, or more. The radiation plan provided that all circuits function beyond 150 krads inside the circuit box, a factor of two safety. Therefore Galileo should function to orbit 14 at the minimum. Additionally, for purpose of design, radiation failure was deemed to occur at the dose 3-sigma below the average device failure dose, another margin of safety unless one had a maverick device in an important circuit. The 3-sigma safety margin may again double the spacecraft life to perhaps 300 krads late in 1999. The Galileo has survived even that. Another hidden safety factor occurs because device failure is deemed to occur when the device drifts outside its performance specifications. But circuit designers usually provide substantial margin beyond the device specs so that the systems live when devices go well out of spec. Perhaps this hidden margin provides another factor of two for Galileo radiation performance so that failure won't occur until sometime in 2001. Radiation damage is known to often partially anneal. Rarely is this evaluated. Finally, many devices are not operated at their worst radiation-sensitive bias conditions, and actually go out of spec at much higher doses than predicted. Does this give us another factor of two?? Will Galileo operate until 2003?

LESSONS LEARNED FROM GALILEO

The General Radiation Environment is variable, at least a factor of two relative to the mean. Short-lived missions might experience a very hot environment.

The Specific environment, flux as a function of energy and direction, are modeled but not well confirmed. The very high-energy deeply penetrating flux is most uncertain, yet most critical for spacecraft design.

For a fixed environment, the radiation transported to a sensitive device is uncertain due to the complexities of shielding mass distribution, spacecraft orientation, and simplifying assumptions in the transport calculation. Uncertainties are at least 20%, perhaps factor of two at deep penetration.

On-board dosimetry, not space radiation spectrometers, is needed to evaluate actual dose-depth on spacecraft in this environment so that tighter spacecraft radiation design can be achieved.

Actual operating conditions may be the most important parameter to specify for radiation ground test procedures. System life may be greatly extended by choosing the best operating point of sensitive devices. Soft devices may be hard at some operating conditions.

Radiation failure should be described as parameter shifts in operating devices. The shifts should be described thus allowing designers to include in-service adjustment of the instruments.

The hidden safety margins should be evaluated to determine if soft devices might be acceptable.

Safehold events on Galileo had a time cushion up to two months before again passing close to Jupiter. This provided operators time to fix the mission. In practice this highly eccentric kind of orbit provides a large safety margin. More traditional low circular orbits would require rapid fixes in order to complete the mission before radiation kills a Jovian spacecraft.